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14. ABSTRACT

In this work, efforts were concentrated upon exploration and examinations of the impedance parameter space and output pulse characteristics of the Blumlein devices to facilitate development of reliable pulsers capable of generating intense ultra wideband electric fields. Output pulse characteristics available from our Blumlein pulsers with different number of lines, line impedances and switching devices were examined. The range of pulse characteristics that may be of interest for Bioelectric and Isomer Research applications were recorded. Issues concerning the switch longevity were studied by fabrication and testing the GaAs photoconductive switches treated with the amorphic diamond. Longevity tests were performed and results for the switch lifetime demonstrated a significant improvement with the application of amorphic diamond. In addition, we studied and surveyed various methods and geometries for non-intrusive electric field delivery and flash x-ray production. Low impedance x-ray diodes designed and implemented. Output waveforms and x-ray generation were examined by the proper matching of diodes to Blumlein pulsers commutated by thyratrons and or photoconductive switches. Ultra-fast rising x-ray pulses were produced and studied.

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INTRODUCTION

In recent years the new field of Bioelectrics has opened a wide range of application areas for pulsed power research and development. Intracellular electromanipulation involves bioelectric processes that require the development of reliable pulsed power sources that produce fast electric fields preferably larger than 30 kV/cm at pulse durations in the nanosecond range. Initial approaches by Schoenbach, et al [1] to apply pulsed electric fields to kill cells by apoptosis has demonstrated success. There, as the applied pulse duration decreased from 300 ns to 10 ns, electric field effects were reduced at the level of the plasma membrane and were focused to the cell interior. At the high enough electric field intensities apoptosis could be induced as indicated by the reduced size of treated mouse tumors [1]. This type of field-cell interaction using nanosecond pulses with high electric field has proved potential to affect transport processes across sub-cellular membranes and it has been widely experimented in last couple of years [2]. These studies have demonstrated that triggering of the intracellular processes could be used for cancer treatment by programmed cell death.

It should be noted that the utilization of pulse power technology to treat cancer in human subjects ideally would use non-intrusive methods such as ultra-wideband (UWB) transmitters. These devices radiate fast-rising electromagnetic pulses with durations in the range of nanoseconds. They could be used to provide necessary electric field strengths and durations at a tumor location in human body to promote enhanced chemotherapy and cancer treatment. Recent investigation in this direction has demonstrated that UWB radiation results in immediate non-thermal killing of Jurkat cancer cells in the absence of hallmarks of apoptosis including caspase activation and fragmentation of chromosomal DNA [3].

The development of UWB sources has been pursued in two general directions. The first uses a single pulser to feed a very high voltage to a single antenna transmitter. The pulser can be used to feed a non-dispersive high gain antenna system to achieve high field strength in the far field of the antenna. The second approach employs many radiating elements (array UWB source) switched at relatively low voltage to collectively deliver an additive field at the target of the array. The photoconductive semiconductor switched (PCSS) array method has been employed and demonstrated in the systems such as GEM series of pulsers at the U.S. Air Force Research Laboratory [4]. In addition to the military applications, such UWB schemes can provide non-intrusive probe of human body for medical treatments if suitable electric strength can be arranged.

Blumlein pulse generators are most suitable for the intracellular electromanipulations applications in the Bioelectrics field because they have low inductance geometry that permits generation of fast rising waveforms easily matched and delivered to the relatively low impedance biological loads or radiating antennas.

One of the new research directions currently opening involves the modulation of nuclear properties. Of particular interest are nuclear spin isomers. They store the highest densities of energy possible without nuclear reactions. For example, an isomer of ^{178}Hf stores 2.445 MeV per atom for a shelf life of 31 years. However, in nuclear spin isomers the energy is stored electromagnetically so that it would be released as x-rays and γ-rays, if it could be triggered. Since isomers derive their long shelf lives from their poor coupling to electromagnetic waves, it was traditionally thought to be impossible to trigger the release of the stored energy. Recent reports [5,6] in Isomer Research has demonstrated a way of excitation to couple energy into $^{178}\mathrm{Hf}^{m2}$

isomeric nuclei causing excitation from the long-lived isomeric state to a state with a much shorter lifetime.

Important to the success of the Isomer Research is the in-house accessibility of a source of pulses of x-ray of short duration that is very powerful in comparison with conventional devices. In recent isomer experiments, the isomeric targets were irradiated with x-rays photons at the SPring-8 synchrotron radiation facility [5,6]. Synchrotrons such as Spring-8 have the advantages of collimation and tunability. However, these devices are few in number and require complex supporting facilities resulting in experimental time being at a premium.

During this research project, we explored the impedance parameter space and output pulse characteristics in our Blumlein pulsers and modulator pulse forming lines to in order to enlarge the pulser technology base, level of understanding and design options and to facilitate development of reliable pulsers capable of generating intense ultra-fast electric fields and or x-ray pulses with nanosecond durations suitable for applications in the fields of Bioelectric and Isomer Research.

BLUMLEIN PULSE GENERATORS

The Blumlein pulsers developed at the University of Texas at Dallas (UTD) consist of either a single or several triaxial Blumleins. For multiple lines, Blumleins are stacked in series at one end and charged in parallel and synchronously commutated with a single switching element at the other end.

1) Pulser Design and Characteristics-General Review

Design and construction of the pulse forming system for the Blumlein generators have been given elsewhere [7-9]. Briefly, a single Blumlein pulse generator consisted of a single Blumlein pulse forming line, and a commutation system capable of operation at high repetition rates. To access voltages above 100 kV, number of stacked Blumlein pulse generators were designed and constructed [7]. Their basic organization consisted of three separate but integrated subassemblies: (1) the switching assembly, (2) pulse forming Blumleins, and (3) the pulse stacking module. A photograph of a simple 2-line stacked Blumlein pulse generator switched with a spark gap is shown in Fig. 1.

The Blumleins were constructed from copper plates separated by laminated layered Kapton (polyimide) dielectrics. Scaling of both single and stacked Blumlein devices were studied by construction of several separate systems with different lengths, capacitances, and impedances [7,9]. In operation, the middle conductor was charged to a positive high voltage that could be varied to 75 kV, and commutation was affected by a fast switching element such as a spark gap. To characterize the pulsers two modes of open circuit and resistive loading conditions were implemented. In addition, different types of switching devices with different voltage hold off characteristics were used. This resulted in peak voltages available at the load that spanned the range from 5 to 550 kV. The voltage waveform available from a 6-line pulser commutated by a thyratron in the resistive loading condition of operation is shown in Fig. 2.

2) Photoconductively-Switched Pulsers

Our recent efforts have resulted in implementation and demonstration of several intense photoconductively switched stacked Blumlein pulsers. Presently, these devices operate with a switch peak power in the range of 50-100 MW and activating laser pulse energies as low as 300 nJ [10]. Examinations of output waveforms have indicated pulse durations in the range of 1-5 ns and risetimes as fast as 150 ps. An example of the output voltage generated by a 2-line pulser in both resistive loading and open circuit modes of operation shown in Fig. 3. A GaAs PCSS and a charging voltage of 40 kV were used to obtain these waveforms. The peak resistive voltage corresponded to 72 kV at the matched impedance of 200 Ω. The peak open circuit voltage was 130 kV.

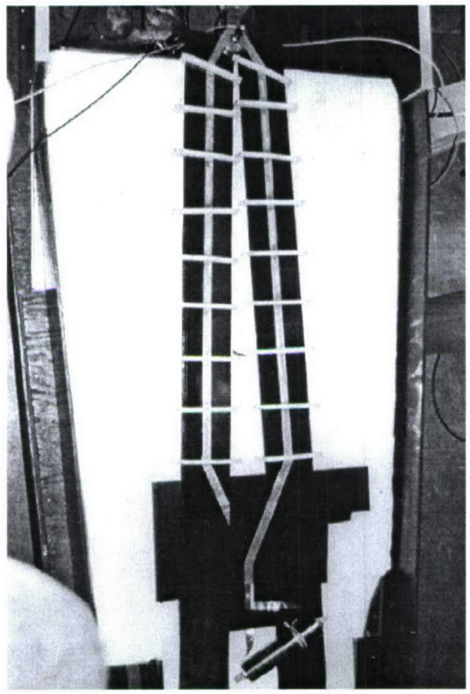

Figure 1. Photograph showing a top-view of a 2-line pulser commutated by a spark gap.

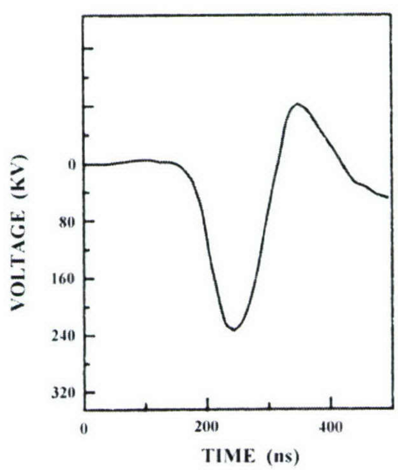

Figure 2. Output resistive load voltage waveform generated by a 6-line stacked Blumlein prototype pulser commutated with a thyratron. This particular pulse correspond to a charging voltage of 50 kV.

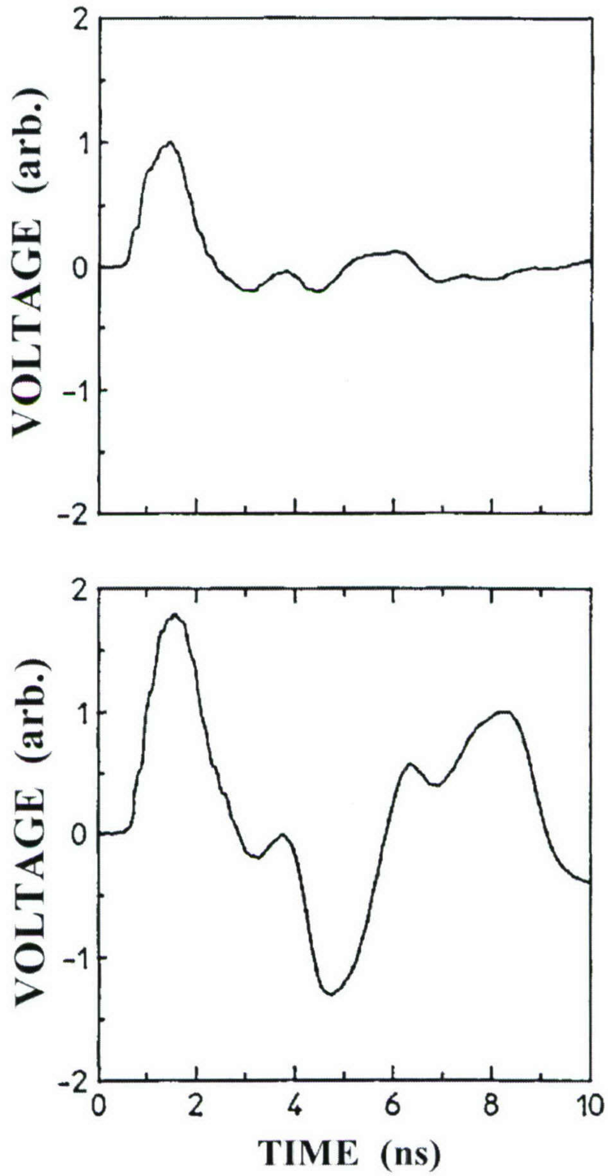

Figure 3. Output voltage waveforms obtained by operating a 2-line pulser with (top) matched resistive load and (bottom) open circuit with no load. Device was operated with a charging voltage of 40 kV.

A 4-line pulser was designed and constructed by combining two units of 2-line device. The commutation assembly was reconfigured to contain two sets of electrodes. The pulse forming lines in each 2-line unit were bent in a manner to bring the stacking sections to the same location one above the other. The units were joined in series and the top and bottom plates were connected to a resistive load built from a stack of four 100 Ω, non-inductive carbon disc resistors. This pulser was synchronously commutated by two GaAs PCSS and was capable of producing 1.5 ns output pulses with risetimes in the range of 200-500 ps. A photograph of this pulser is shown in Fig. 4. Table 1 present the best simultaneous results obtained, to date, by switching the stacked Blumlein pulsers with a high gain GaAs photoconductive semiconductor switch (PCSS).

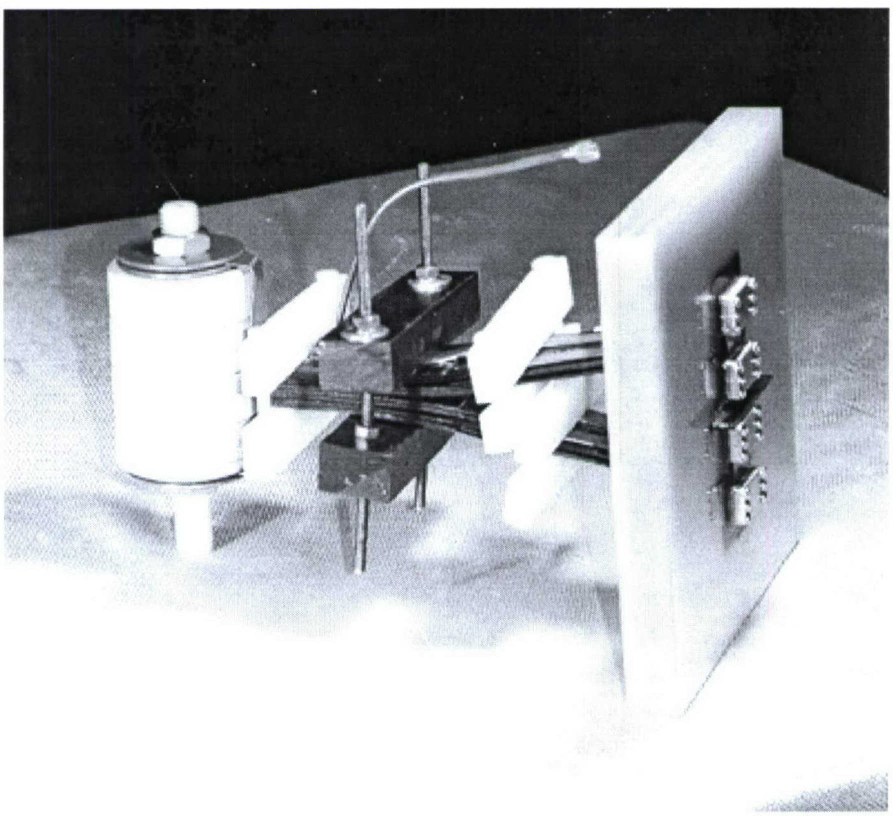

Figure 4. Photograph showing a 4-line pulser commutated by two photoconductive switches.

Table 1. Best simultaneous results obtained by commutation of the 2-line stacked Blumlein pulsers with the high gain GaAs switches

Parameters	Simultaneous Results		
Switch Voltage	60 kV	30 kV	15 kV
Switch Gap	10 mm	5 mm	2.5 mm
Switch Current	1.2 kA	0.6 kA	0.3 kA
Pulse Risetime	200 ps	200 ps	200 ps
R-M-S Jitter	500 ps	500 ps	500 ps
Optical Trigger	300 nJ	300 nJ	300 nJ
Repetition Rate	10 Hz	20 Hz	20 Hz
Electric Field	60 kV/cm	60 kV/cm	60 kV/cm
Stack Voltage	112 kV	57 kV	29 kV
Switch Lifetime	2×10^4 pulses	3×10^5 pulses	4×10^6 pulses

3) Photoconductive Switch Design

During the avalanche-mode photoconductive switching of the Blumlein pulsers, the current is concentrated in filaments that extend from the cathode to the anode across the insulating region of the PCSS. Filamentary currents with densities of several MA/cm^2 and diameters of 15-300 μm passing through a narrow channel can cause switch damage, especially at the contacts points. A greater number of filaments during each cycle of commutation reduce the stress on the switch, thereby increasing its lifetime. One of the objectives of this research project was to implement the broadening of the current channels by application of amorphic diamond coatings to the PCSS switch electrodes in order to enhance operation and switch lifetime in Blumlein pulse generators.

Basic research in our laboratory has developed a conformal coating that has the hardness of natural diamond. This material has been termed amorphous ceramic diamond and later shortened to "amorphic diamond" for convenience. Deposited at room temperatures it forms a strong bond to any material onto which it is applied. Such a favorable combination of hardness, chemical bonding and elasticity should translate directly into an increased resistance to abrasive wear of components coated with amorphic diamond. It has been shown that only a 1-3 μm coating of amorphic diamond could protect fragile substrates against erosive environments [11,12].

Analytical techniques have shown amorphic diamond to consist of nodules of tens of nanometers in diameter that are composed of sp3 (diamond) bonded carbon in a matrix of other carbons. The diamond character has been confirmed by the agreement of structural morphology, density, optical properties, K_{α} line energies and hardness. Since it is produced under conditions that are also optimal for the growth of interfacial layers, the films of amorphic diamond are strongly bonded to the substrates onto which they are condensed [11,12].

It has been determined that amorphic diamond emits electrons at high current densities when immersed in modest electric field strengths [13]. By depositing films of amorphic diamond near the switch contacts, the number of carriers and avalanche sites increase aiding the switch performance. In addition, due to mechanical properties of amorphic diamond, damage to the switch at the contact points during commutation is reduced, improving the switch lifetime.

4) Diamond-Coated Photoconductive Switch

During this research, we have studied the current-voltage characteristics for the diamond coated and bare GaAs switch materials with four different gap settings. Electrode copper foils were attached to opposite sides of the switch using conducting silver paint and epoxy. A Keithley 237 high voltage source-measure unit was used to provide constant voltage bias in the range 0-400 V while monitoring the current through the sample. For measurements of forward diode characteristics, diamond coating was biased negative with respect to the substrate.

Figure 5 shows the current-voltage plots for four switches with the different gap settings each coated with a strip of 1-μm amorphic diamond. Forward characteristics correspond to measurements performed with the switch cathode coated with diamond. The reverse characteristics provide the response for the switch with the anode side coated with amorphic diamond and may be used to reduce switch leakage current.

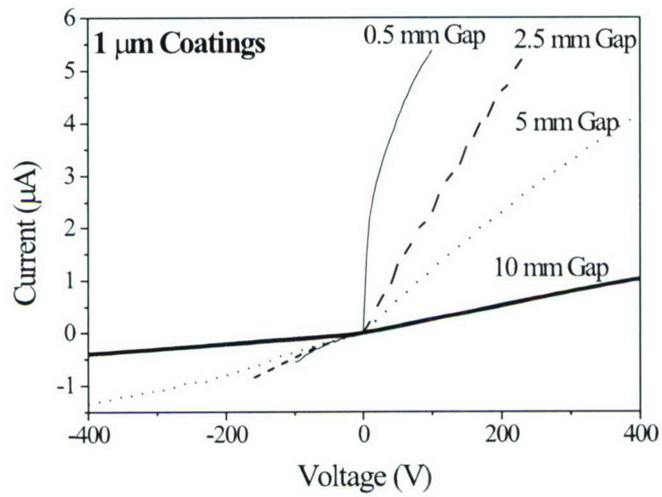

Figure 5. Current-voltage characteristics measured in the dark for three samples of diamond coated GaAs switch substrates with gap settings of 0.5, 2.5, 5 and 10 mm.

The rectifying behavior has been attributed to the amorphic diamond/GaAs heterojunction because the I-V plots for the uncoated samples show symmetrical and ohmic character with change in the voltage polarity. The rapid current increases in the forward direction are due to tunneling of electrons from amorphic diamond to the conduction band of GaAs, a process similar to Fowler-Nordheim tunneling [13]. Our earlier studies have shown that the thicker diamond coatings enhance the current increases in the forward direction and reduce the process of rectification under reverse bias conditions.

Study of the I-V plots in Fig. 5 shows the forward and reverse bias dynamic resistance values are increased and decreased, respectively, as the corresponding switch gap settings is reduced. The trend seen in Fig. 5 is a complex combination of the junction character and the dynamic resistance of bulk GaAs in each switch, especially for the reverse bias voltages. Examination of the forward I-V characteristics indicates that the dynamic resistance of the bulk GaAs is the dominant factor for the coated sample behavior. For Example the forward conduction current for the sample with a 0.5 mm gap at a particular voltage V is about the same as conduction currents for the switch samples with 2.5, 5 and 10 mm gaps at bias voltages 6, 12 and 24 V, respectively. For the reverse bias condition the I-V behavior is affected by combination of comparable dynamic resistances for the junction and bulk GaAs with a complex de-convolution factor.

The diamond/GaAs heterojunction response is limited to a very thin layer across the cross section between amorphic diamond and GaAs that includes coating thickness. This implies that while the charging voltage applied to the photoconductive switch electrodes during the off-state phase are usually in the range 10-100 kV [7], the actual voltage driving the hetrojunction behavior could be as little as only a few volts.

The effect of diamond coating on off-state switch conduction is a combination of the heterojunction behavior and the bare GaAs performance under bias voltages applied. Thus, the I-V behavior of the diamond coated switch with the 2.5-mm gap setting should be about equivalent to that of the coated switch with the 0.5 mm gap combined in series with an uncoated switch with a 2.5-mm gap. Similarly, the characteristics of diamond-treated switches with the 5-mm and 10-mm gaps are about equivalent to the coated switch with 0.5-mm gap plus an uncoated switch with 5-mm and 10-mm gaps, respectively. Furthermore, the I-V behavior of the coated switch with the 10-mm gap is equivalent to the coated switch with the 5-mm gap plus an uncoated switch with a 5-mm gap. These assertions were found to be accurate by study and examinations of I-V plots such as those shown in Fig. 5.

5) Switch Performance and Lifetime

During period of this project, we studied the lifetime of GaAs switches with a 1-cm strip of 0.5-μm diamond coatings deposited on the switch at electrode locations: cathode, or anode, and/or both cathode and anode. All switches were installed in an opposed configuration where the electrodes were attached to opposite sides of switch and so conduction was through the bulk of GaAs. Commutation of the switch was triggered at 905 nm by focusing a laser diode array beam in two straight lines across the switch gap from cathode to anode. For these studies we used a photoconductively-switched 2-line stacked Blumlein pulser.

Three switch gaps of 2.5, 5 and 10 mm were chosen for this study. The switch lifetime tests were performed at switch voltages of 60, 30 and 15 kV with switch gap settings of 10, 5 and 2.5 mm, respectively so that the switch electric field remained 60 kV/cm in all the cases studied in this work. Under similar conditions of experiments and switch configuration, we also performed switch longevity experiments with uncoated GaAs switches. Results of these studies given in Table 2 indicate significant switch lifetime improvement by the application of amorphic diamond. In all cases, it is demonstrated that diamond coating of either cathode or anode location improve the switch longevity. However, it appears that application of amorphic diamond to cathode area results in longer switch lifetimes as compared to applying diamond films only to anode location. In addition, the diamond treatment of both anode and cathode locations improve the lifetime further as compared to treating only cathode or anode area. As expected, the switch longevity strongly depends on switch current. In this work, the switch lifetime improved by factor of about 2 orders of magnitude with reducing switch gap setting from 10 mm to 2.5 mm corresponding to switch current reduction from 1.2 to 0.3 kA.

Table 2. Results of diamond-treated switch longevity tests

Test Condition	Switch Lifetime 2.5 mm gap	Switch Lifetime 5 mm gap	Switch Lifetime 10 mm gap
Uncoated Switch	1×10^5 pulses	1×10^4 pulses	1×10^3 pulses
Diamond coating at anode	5×10^5 pulses	4×10^4 pulses	3×10^3 pulses
Diamond coating at cathode	1×10^6 pulses	1×10^5 pulses	1×10^4 pulses
Diamond coatings at both anode and cathode	4×10^6 pulses	3×10^5 pulses	2×10^4 pulses

For comparison the negative photographs of the electrode areas for switches with 5 mm gap are shown in Fig. 6 after 10^4 shots. The appearance of damage is consistent with the results of longevity tests presented in Table 2. It appears that the damage at the electrode contact areas eventually caused thermal runaway at the switch gap surface and produced a crack that shorted the gap. In experiments where the switch had no diamond coating, the majority of the time, a single current filament commutated the switches. The filament was initiated near the cathode and followed the focused laser beam path to the anode. Multiple branching was rarely seen [7]. In the case of the switch with diamond coating, the multiple branching was observed more often, indicating an increase of pre-avalanche sites.

Control of the current conduction flow at the interface between amorphic diamond and PCSS material has pronounced effect upon the off-state switch hold-off and switch performance. For example, the tunneling of electrons from amorphic diamond to GaAs during the off-state stage of PCSS operation provides pre-avalanche sites that diffuse conduction current upon switch activation. Furthermore, as indicated in Table 2, the diamond coating of the switch anode area has resulted in increased hold-off characteristics of the PCSS in the off-state stage of operation leading to longer switch lifetimes. In this case the amorphic diamond inhibits the flow of electrons at the interface until very high fields are reached. This is due to rectifying behavior of the amorphic diamond/GaAs heterojunction operating under reverse bias condition as discussed earlier in this report.

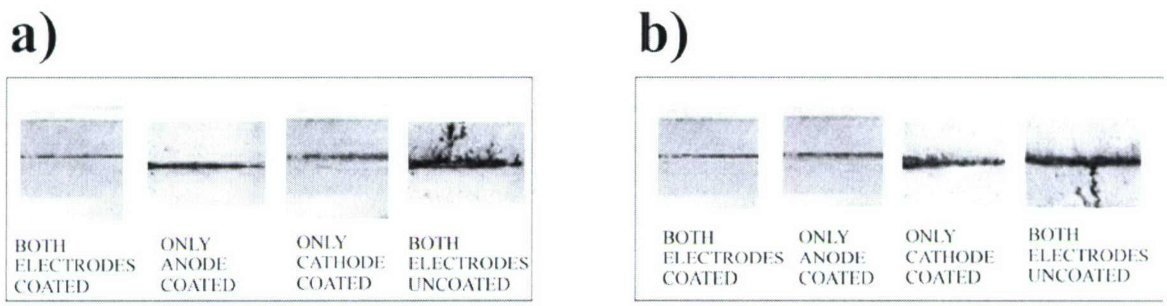

Figure 6. Appearances of damage on a) cathode location and b) anode location of the switches with 5 mm gap. For comparison the negative photographs of the switch electrode areas for the diamond-coated and uncoated switches are shown after 1 x 10^4 commutation cycles.

The semiconductor properties of amorphic diamond have been employed to significantly improve the PCSS longevity by coating the switch cathode or anode areas or both. Further lifetime improvements are anticipated by designing a switch with parameters that make optimal use of amorphic diamond coatings for long-life operations of avalanche PCSS. Design options include: switch configuration, switch gap setting, diamond film thickness, exact locations of diamond coatings and diamond film qualities.

PULSER OUTPUT CHARACTERISTICS

Our Blumlein pulsers have progressed from relatively simple, single-line devices to the most recent, compact stacked systems. Extensive characterizations of performance have demonstrated the versatility of these pulsers. It is shown that they can be developed into light and compact devices without degradation in their performance [7]. With slight design modifications, they can produce waveforms with a wide range of pulse durations and peak values. Table 3 summarizes the output pulse characteristics available from our Blumlein pulsers. The open circuit waveforms available resemble that of Fig. 3 with corresponding peak voltages and pulse risetimes given in Table 3.

Table 3. Summary of the output characteristics for Blumlein pulsers

Blumlein Pulser Configuration	Switching Device	Output Characteristics				
		Impedance (Ω)	Pulse Duration (ns)	Pulse Risetime (ns)	Peak Voltage matched (kV)	Peak Voltage Open Circuit (kV)
Single-Line	Thyratron	1- 200	50-100	10-40	5-75	8-140
	Spark Gap	1-200	20-100	4-10	5-75	10-130
	Photoconductive Switch	50-100	1-40	0.15-1	10-60	15-110
2-Line Stacked	Thyratron	40-100	50-600	15-40	10-120	18-180
	Spark Gap	40-100	20-100	5-15	10-110	20-200
	Photoconductive Switch	100-200	1-5	0.2-1	30-120	45-160
3-Line Stacked	Thyratron	60-150	50-100	20-40	15-170	25-300
	Spark Gap	60-150	20-100	5-20	15-170	30-280
4-Line Stacked	Thyratron	80-200	50-100	25-40	20-190	30-350
	Spark Gap	80-200	20-100	8-20	20-195	30-340
	Photoconductive Switch	400	1.5	0.2-0.5	50-150	80-200
6-Line Stacked	Thyratron	120-300	50-100	25-50	30-270	50-500
	Spark Gap	120-300	20-100	8-25	30-260	55-480
8-Line Stacked	Thyratron	160	150	70	40-310	70-420
12-Line Stacked	Thyratron	480	200	75	60-400	100-530

It should be noted that the pulse characteristics listed in Table 3 are of great interest for Bioelectrics applications. For example, the outputs from the low impedance pulsers could be used to directly match to biological loads for study of intracellular studies. The open circuit pulses exhibiting bipolar shapes such as that seen in Fig. 3 could also be delivered to the mismatched biological cell suspensions and may be utilized to study bipolar-UWB radiation effects on chemotherapy of cancer cells [3]. Moreover, we would like to emphasize the capability of these pulsers for generating UWB waveforms by matching the outputs to radiating antennas.

There has been a great progress in development, and optimization of impulse radiating antennas (IRA) in recent years. Numerous IRAs with different characteristics such as input impedance, effective gain, field strength and uniformity have been produced [14,15]. The Blumlein pulsers described in this work may be ideal for use with available IRAs. As indicated in Table 3, a wide range of output impedances and characteristics are accessible that may be used with a particular IRA to radiate a necessary field strength for non-intrusive Bioelectrics applications. For example an array UWB radiation would simply be realized by the split of a 200 Ω output into four 50 Ω lines each matched to a separate IRA. One may also use a particular stacked Blumlein pulser without stacking the lines. In this case, individual IRAs matched to each line could simultaneously radiate electric fields in an array fashion.

FLASH X-RAY PULSES PRODUCED BY BLUMLEIN DEVICES

Important to the success of the isomer research is the in-house accessibility of a source of pulses of x-ray of short duration that is very powerful in comparison with conventional devices. In recent isomer experiments, the isomeric targets were irradiated with x-rays photons at the SPring-8 synchrotron radiation facility with energies tuned from 9-13 keV [5,6]. Synchrotrons such as Spring-8 have the advantages of collimation and tunability. However, these devices are few in number and require complex supporting facilities resulting in experimental time being at a premium.

1) Review

Flash x-ray systems have long been known as useful radiation sources for investigation of high-speed phenomena. Currently a variety of pulse x-ray machines with different characteristics such as energy spectra, average x-ray powers and pulse duration are in use. For some application emphasis is being placed on spatial resolution or energy characteristics while others may be concerned with the temporal aspects of the radiation source.

The use of electron accelerators as source of synchrotron radiation has grown enormously during the last decade. Average x-ray powers can now be great enough so that many experimental responses can integrate above the noise in reasonable working periods. Unique features such as collimation of the output tend to render the synchrotron irreplaceable for many applications. Nevertheless, the imbalance between demand and supply of such facilities has motivated the development of alternative laboratory sources for some applications not needing all the distinctive features of a synchrotron.

Laser-driven generators produce x-ray in the soft x-ray region. However, conversion efficiencies are substantially reduced for the production of plasmas radiating x-rays in the wavelength region of less than 5 Å. E-beam machines offer maximal emitted power per shot in x-ray region. Utilizing large scale Marx technology, these machines generate tremendous x-ray fluxes with pulse widths on the order of 10 ns. Since they usually have low repetition rates, their usefulness is limited in experiments dependent upon the integration of responses that occur with low probabilities.

An x-ray source incorporating many of the desirable characteristics of these systems into one device would be extremely useful. For the past several years our group at UTD has been involved in development and characterization of compact Blumlein pulse generators. These devices are capable of producing high power waveforms with pulse durations, risetimes and repetition rates in the range of 1-600 ns, 0.1-50 ns and 1-300 Hz, respectively, using a conventional thyratron, spark gap, or photoconductive switch. Voltage and current amplitudes in the range of 10-600 kV and 0.1-20 kA, respectfully have been produced. Blumlein pulsers have been used to drive x-ray diode loads with different characteristics and discharge geometries. High dose rates of x-rays with pulse duration in the range 3-20 ns have been obtained using a thyratron or a spark gap as the switching device. Here, the technology and characteristics of these Blumlein based flash x-ray devices are given and reviewed.

2) Flash X-ray Devices Powered by Blumlein Pulse Generators

A major step in the development of intense pulsed power supplies with the elimination of the output switch, the element which most critically limits the repetition rate of firing was reported by our group [16]. Developed to power pulsed x-ray diode for the excitation of nuclear fluorescence, we succeeded in switching a 1 Ω Blumlein with a hydrogen thyratron at a repetition rate of 100 Hz. Higher average x-ray powers were obtained both by scaling these devices in size and by operating them at higher charging voltages [17]. The spectral content of the fluxes emitted by different anodes was measured reliably. A third of the energy was found to be in K lines. The remainder was distributed over a fairly broad band of true continua with the endpoint energy lying above the charging voltage of the Blumlein circuit. The combination of all aspects in the development of these devices resulted in an x-ray source with an energy range that spanned from 5 to 100 keV. Operating parameters for these single Blumlein pulse power devices were constrained by the limitation on peak currents and the voltage tolerances of existing commercial thyratrons.

To access higher voltages, we reported construction and characterization of a laboratory scale pulse generator, driven by stacked Blumleins [18]. It had eight Blumleins which were charged in parallel at one end and switched with a single thyratron. Scaling of such an impulsive device to potentials exceeding 400 kV, while retaining the capabilities for operation at high-repetition rates was reported subsequently [19]. There a second prototype pulse x-ray generator, driven by stacked Blumleins was described. An extensive characterization of the performance of this pulse power device was given. Improvements in the design and construction of this device resulted in better voltage gains and it was noted that the maximum number of lines that can be stacked had not been reached. An x-ray diode matched to this power source allowed the production of intense x-ray pulses containing useful fluxes of photons having energies of 300 keV [19]

3) Flash X-ray Diodes

Blumlein Pulse Power sources developed at UTD have been mainly used to drive x-ray diode loads. Several x-ray diodes have been constructed with a variety of materials and discharge geometries. Reasonable matching of these heads to the pulse generators has allowed production of high power x-ray pulses with durations as short as 20 ns [16,17]. Two basic diode configurations for low-voltage and high-voltage operations have been used. With emphasis on obtaining a singularly low inductance input to electrodes designed to give a filamentary source of radiation, the x-ray tube for use with single Blumlein pulser was constructed from cast materials selected to minimize erosion and maximize heat transfer. Copper foil strips 0.05 mm thick and 10 cm wide were fastened to the electrode mounts, then passed through the cast material of the base of the x-ray head before it hardened, and finally joined to the outermost copper plates of the Blumlein. In this way any transverse constriction of the path of the discharge current between the Blumlein and the electrodes was avoided.

The design of the x-ray tube for the low-voltage operation has evolved substantially from that used in earlier models where the anodes had been cast directly into the base to facilitate passage of the connecting foil [16]. However, the potential need for the use of exotic anode metals made it necessary to develop the capability shown in photograph of Fig. 7 for the interchangeability of anodes. In this design the anode is a simple cylinder of metal, 6.35 mm in diameter and 10 cm long, which is inserted into a socket as shown. The cathode is also demountable. It consists of a strip of 0.381-mm-thick graphite further ground with a bladelike edge 10 cm wide and is separated from the anode by a variable distance chosen to optimize performance. The electrical length of the strip was selected to give a resistance comparable to the line impedance but below it in order to assist in damping the ringing of the discharge current in the period following the initial pulse that produced the x rays. The position of the line of intersection between the mid-plane of the current sheet and the anode surface proved to be an important parameter, most probably because of a potential compensation between the angular distribution of the emitted x rays and the possible shadowing effect of the anode rod for some relative positions. Shims were inserted to raise the cathode blade in order to maximize the output. This type of low-voltage diode was also used with stacked Blumlein pulsers producing output voltages less than 150 kV.

The x-ray diodes for high voltage operation were constructed from carefully selected cast materials as the thermal and electrical stresses were substantial in repetitive discharges approaching 500 kV and 1 kA. Copper foil strips, 5 cm wide and 0.4 mm thick, were fastened to electrode mounts and passed through the cast material of the base before it hardened. A thick kapton laminate 1.2 cm wide separated the anode and cathode in the discharge area, continuing back through the cast and into the Blumlein stack as shown in Fig. 8. This dielectric wall emerged from the back of the case as did the foils. The gap between the foils was such that they could slide straight in and smoothly enter the stack. A diode with electrodes in the transmission geometry was used as seen in Fig. 8.

The anode-cathode gap was adjusted until greater than 85% of the peak open circuit voltage was transferred to the electrodes during x-ray production. To maintain short-pulse widths, the electron extraction from the cathode was enhanced to provoke a fast decay of tube impedance. A sharp-edged, graphite cathode was used to generate high fields and to efficiently emit electrons. Several kapton insulator rings were also cast into the head to decrease surface arcing.

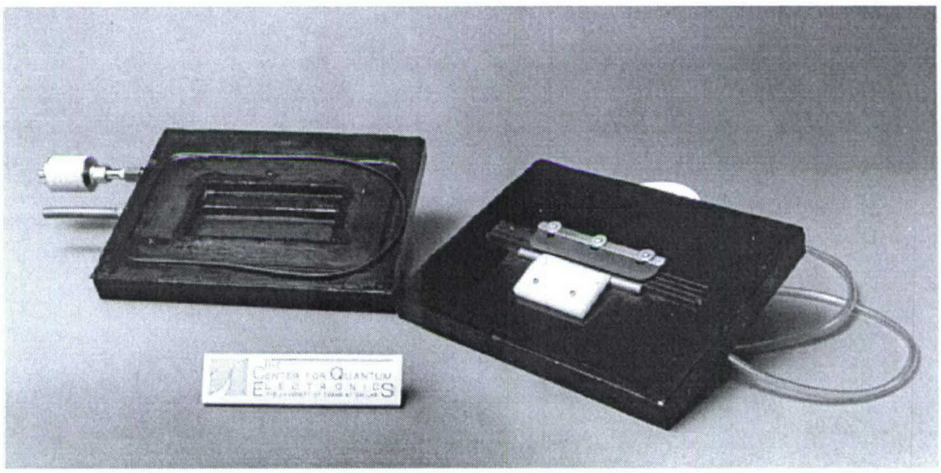

Figure 7. Photograph of the low-voltage x-ray diode used with Blumlein pulse generators commutated by a thyratron or a spark gap.

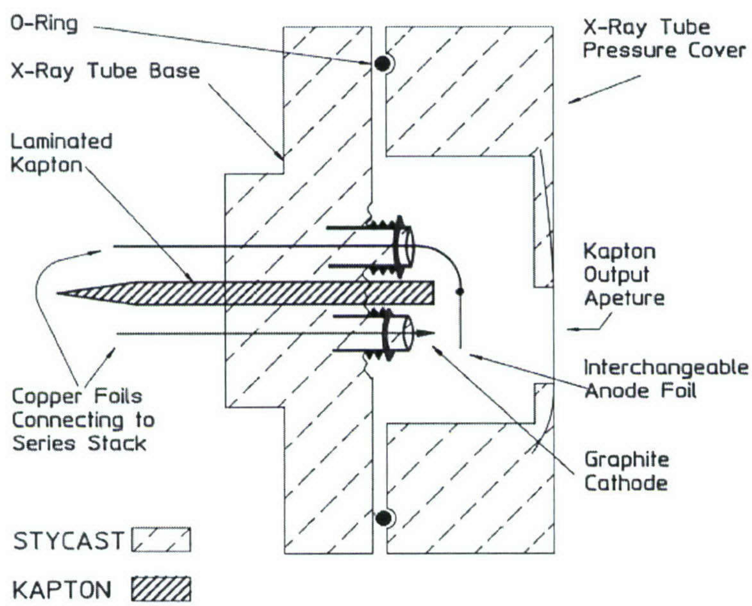

Figure 8. Schematic drawing of a cross section of the high-voltage x-ray diode used with the stacked Blumlein pulse generators.

The discharge space for both types of diodes was enclosed by a pressure shell as shown in Figs 7 and 8, also fabricated from cast materials, with an integral window of 0.076-mm-thick Kapton plastic film. The window aperture was covered with a graphite plate 0.127mm thick to eliminate the emission of visible and UV light. Even with the cast construction and ready access to internal electrode spacings, operating pressures below 3.0 mTorr were routinely maintained with a small mechanical pump.

4) Flash X-ray Production and Characteristics

Characterizations of the flash x-ray systems driven by Blumlein pulser have been given in detail elsewhere [16-19]. Compact flash x-ray sources producing dose rates exceeding 1 kR min^{-1} have been realized utilizing single Blumlein pulsers as the power source [16,17,20]. Interchangeability of discharge anodes has provided for a significant fraction of the output to be extracted in the K lines of Cu, Mo, Nb, and Ag. In less than 1 min of experimental time, a peak spectral density is radiated from these devices that exceeds 1×10^{18} keV/keV [17]. The results of scaling studies have shown that the principal variables determining the temporal morphology of the output x-ray pulse for these Blumlein-driven diodes are actually the electrode spacings. This implies that the basic pulse shapes are determined by the characteristics of the process of closure of the diode gap. The intensity level and thus, ultimately, the energy emitted into the output pulse seems to scale most strongly with the charge voltage. Unlike the analogous cases of laser driven by low-impedance Blumleins, there appears to be no detrimental effect upon efficiency to result from operation at higher repetition rates. Having no gas to heat in the discharge or to sustain shock waves, such favorable contrast with laser performance as observed in our x-ray diodes is actually to be achieved.

The temporal evolution of the x-ray output from the high voltage diode is shown in Fig. 9, together with the time dependence of the open circuit and discharge voltages and the current at the diode. The diode type was similar to that shown in Fig. 8 and stacked Blumlein pulser switched with a thyratron was used as the power source [19]. For this measurement, the curves for x-rays and discharge currents were obtained with a p-i-n diode and a fast current transformer, respectively. Both were directly coupled to a Tektronix 7912AD digitized oscilloscope. Synchronization was readily maintained between records of these waveforms. Because of the higher discharge voltages realized in the transmission geometry of the diode, bremsstrahlung production was peaked in the forward direction. The characteristic x- ray production of lines, however, remained isotropic and was further attenuated by the anode foil. The combination of these effects resulted in an x-ray output containing less than 2% characteristic radiation.

Methods of x-ray spectroscopy inapplicable to single shot systems have been used to record the spectral contents of the outputs. Figure 10 shows typical spectral distribution of fluxes emitted from x-ray diodes matched to the single line and stacked Blumlein pulse generators. A low-voltage configuration was used in the x-ray diodes matched to the single line pulse generators [16,17]. With this type of diode geometry, about one-third of the pulse energy appeared in the lines of the anode materials as seen in Fig. 10 (a).

The remainder was distributed over a fairly broad band of true continua. Substantial amounts of photons with energies up to 300 keV were emitted from the high-voltage diode matched to a stacked Blumlein pulser. Output was a true continuum, peaking in intensities of 5×10^8 photons/keV/shot and containing useful intensities of photons having energies of 300 keV as shown in Fig. 10(b). In this case, peak x-ray powers exceeded 10^7 R/S at the output window of the device.

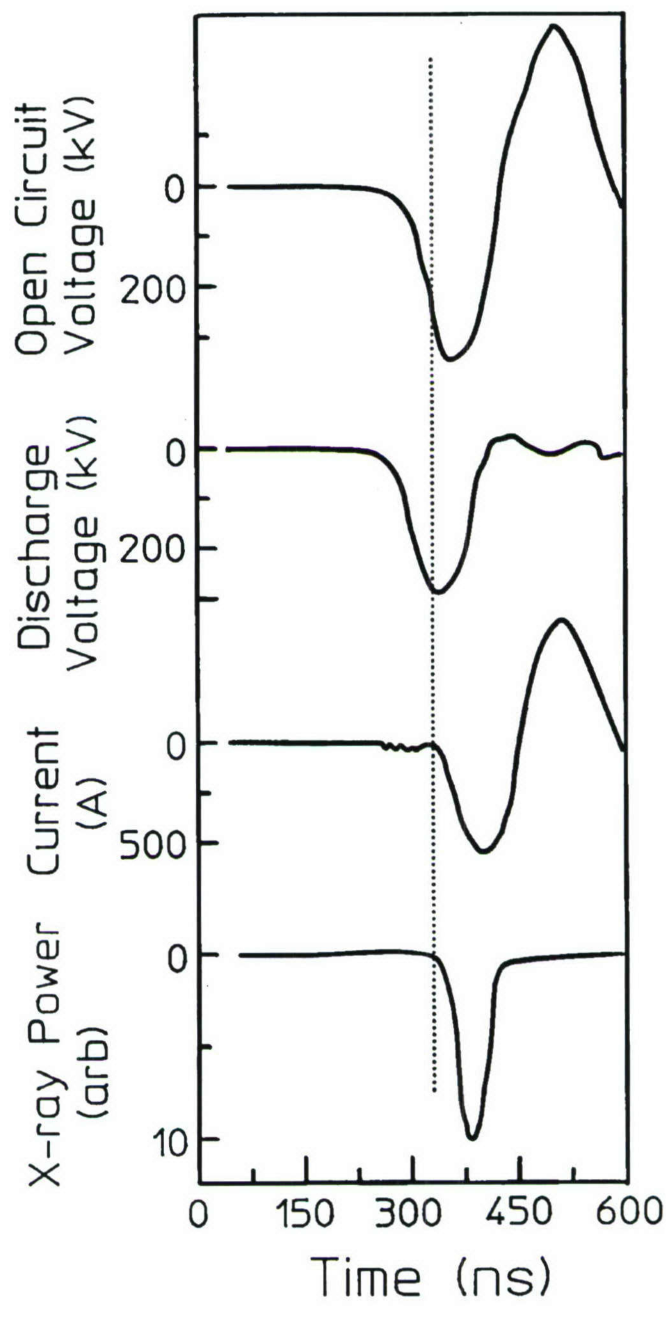

Fig. 9. Typical relationship between the voltages, current, and x-ray output emitted from a high-voltage diode powered by the stacked Blumlein pulser. These particular data corresponded to a charging voltage of 60 kV and an electrode separation of 3.4 cm. The dotted line demonstrates the synchronization of the current and x-ray pulse with the moment when the discharge and open circuit voltages begin to differ.

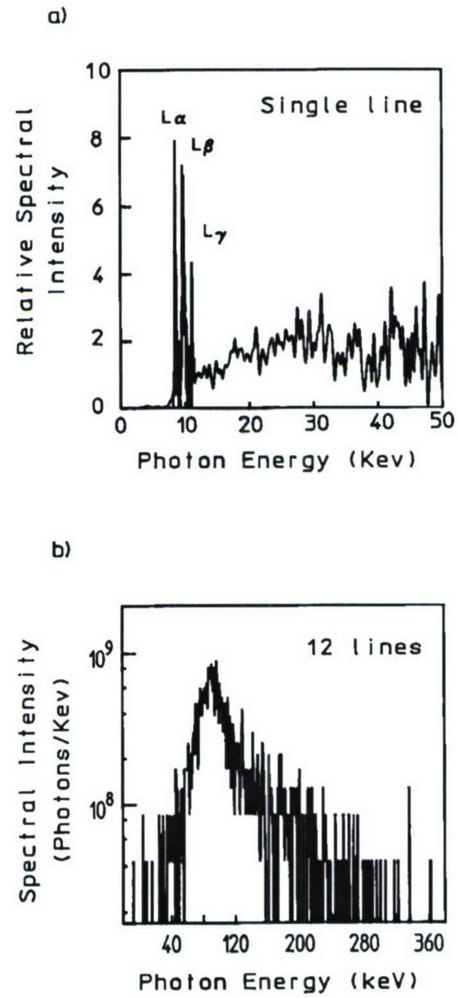

Figure 10. Typical spectral distribution of the x-ray fluxes emitted from the tungsten anode. (a) Spectrum obtained from a diode matched to the single Blumlein pulse generator. (b) Spectrum obtained from a diode matched to the stacked Blumlein pulse generator.

Our current application concerns the use of these flash x-ray devices to excite nuclear transitions where the ultimate signal to noise ratio will depend only upon the total radiation that can be delivered to an extended absorber in a working period.

FLASH X-RAY PRODUCTION CAPABILITIES WITH 100 ps SWITCHING

The match between the power source and the diode is complicated by the rapid collapse of the load impedance during the development of the discharge that has its origins in electrode plasma formation and expansion [21-22]. A self-consistent description of the dominant processes acting within a non-pinching cold-cathode diode at high currents has been provided by others [23]. Cathode processes are thought to determine the initial phase of the diode response and can be described briefly in the following manner. The applied field across the electrodes is enhanced by several orders of magnitude by microscopic projections called whiskers which develop along the surface of the cathode. Due to the high local fields, these whiskers can begin a stable field emission. Electron flow is limited in this phase as emission is constrained to the small area of the whisker tips.

As the electron density increases near these sources, the negative charges present an opposing field which retards the emission of additional electrons. When this field becomes equal to the applied field, the electron flow is said to be space-charge limited. No additional increase in current is possible as the space-charge field would cause the potentials near the cathode to fall below the potential of the cathode itself. The diode impedance is effectively infinite during this time. Resistive heating of the whiskers and evaporation of cathode material into the region immediately beyond the whisker tip follows.

It has been observed that the application of fields in excess of a critical value causes the emission sites to explode within nanoseconds and form cathode flares [19]. The rapid merging of the resultant flares forms a plasma sheath covering the entire cold cathode surface which then moves toward the anode at a constant rate in the range 2-3 cm/μs [23]. Since emission is now taking place from the surface of this plasma, its movement corresponds to a decrease in the effective gap of the diode. This in turn causes the impedance of the diode to fall and eventually the diode plasma closes completely. Some studies have suggested [24] that in some diodes with a conical anode, the discharge is dominated by an anode plasma motion. This may have been caused by the high fields near the sharp anode tips located near the cathode. However, in most cases, and especially in flat diodes, closure is caused by the movement of the cathode plasma.

If the pulse applied to the diode by the pulser is long enough, a rapid growth of current is seen as the cathode plasma nears the anode and closes [21]. At this time diode impedance can fall to a value that approximately matches the impedance of the driving source so accelerating voltage remains and x-ray production continues [24]. In the case where the applied pulse is shorter than the time in which the cathode plasma reaches the anode, the diode closure is dominated by the electric characteristics of the pulser and the discharge is source limited. This case seems more consistent with the behavior of our x-ray diodes at electrode separations in which they were pulsed. The expected space charge limited flow corresponded to very small currents flowing for the first 80 ns of voltage applied by the pulser. As seen in Fig. 9, a rapid rise of current started at the time where the discharge voltage began to break from the form of open circuit ringing, and breakdown was initiated. This time is indicated by vertical dotted line in the figure.

As expected, x-ray output started with the rapid growth of current, reaching its peak value near the time of maximum current flow. X-ray production dropped off as discharge voltage fell and ceased. The times required for the cathode plasmas to reach the anode for the diode gap settings were much longer than the duration of the voltage pulses shown in Fig. 9. The x-ray production mechanism was, therefore, source limited. Current oscillation periods were consistent with the inductive ringing times of the voltage at the x-ray diode. This is shown in Fig. 9, which is also indicative of source limited behavior. The peak value of discharge current near the time of maximum x-ray output is interesting and its depends strongly on peak discharge voltage that further confirms the source limited character of current flow during the breakdown in our x-ray diodes.

Comparison of these electrical inputs with x-ray output pulses at a particular electrode separation indicated that as charging voltage increased, diode voltage and current were also increased and x-ray output was optimized. The diode voltage at larger gap settings and lower charging voltages oscillated in a manner resembling the ringing of an open circuit. In this case, only a partial discharge of the energy stored on the Blumleins occurred and a very low x-ray yield was measured. Conversely, at a high charging voltage with small electrode separation, the diode breakdown occurred before any substantial voltage could be developed across the gap and lowered x-ray outputs. A reduction of gap setting improved the match for lower voltage charging and outputs were increased. In contrast for higher charging voltages, in- crease of electrode separation optimized x-ray outputs [19].

The temporal evolution of the x-ray output from a low-voltage diode is shown in Fig. 11, together with the time dependence of discharge voltage at the diode. The diode type was similar to that shown in Fig. 7 and a single Blumlein pulser switched with a thyratron was used as the power source.

1) X-rays with Photoconductive Switching

As described earlier in this report, our recent efforts have resulted in implementation and demonstration of several intense photoconductively switched stacked Blumlein pulsers. Presently, these devices operate with a switch peak power in the range of 50-100 MW and activating laser pulse energies as low as 300 nJ [7,8]. Examinations of output waveforms have indicated pulse durations in the range of 1-5 ns and risetimes as fast as 150 ps.

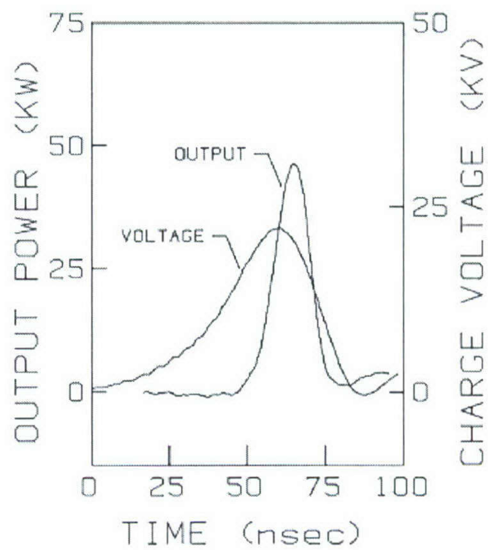

Figure 11. Typical relationship between the voltage and x-ray output emitted from a low-voltage diode powered by a single Blumlein pulser. These particular data corresponded to a charging voltage of 22 kV and an electrode separation of 0.56 mm.

An example of the output voltage generated by a 2-line stacked prototype with Blumlein impedance of about 100 Ω and Blumlein length of 11 cm is given in Fig. 12. Pulse durations of voltage and current waveforms generated were proportional to the Blumlein length corresponding approximately to the two way transit time of Blumleins. Peak voltage value for pulse presented in Fig. 12 was 98 kV and corresponded to a voltage gain of 1.96. Since the stacked Blumlein impedance was closely matched to a non-inductive resistive load, the output current pulse shape, duration and rise time was similar to voltage pulse shown in Fig. 12. Peak current value for the conditions shown in Fig. 12 was about 0.5 kA consistent with the voltage gain and resistive load matching.

In all the Blumlein based flash x-ray systems we have developed, the commutation of pulsers has been affected by a thyratron or a spark gap and the x-ray production was source limited. Furthermore, in all cases under optimized charging voltage and diode gap settings where the impedance of diode matched to the Blumlein pulser, the temporal evolution of pulses followed closely those shown in Fig. 11.

In this work, we explored the use of photoconductively-switched Blumlein devices to produce flash x-rays. The principal challenge was the development of a low geometric profile x-ray diode that could be matched to the Blumlein pulser commutated with a photoconductive switch. Since the resistive load and open circuit voltages have rise times on the order of 150 ps, it is expected that the diode closure would be dominated by the electric characteristics of the pulser and discharge would be source limited. In this case the temporal evolution of diode x-ray output and the time dependence of the discharge voltage at the diode should resemble those shown in Fig. 11.

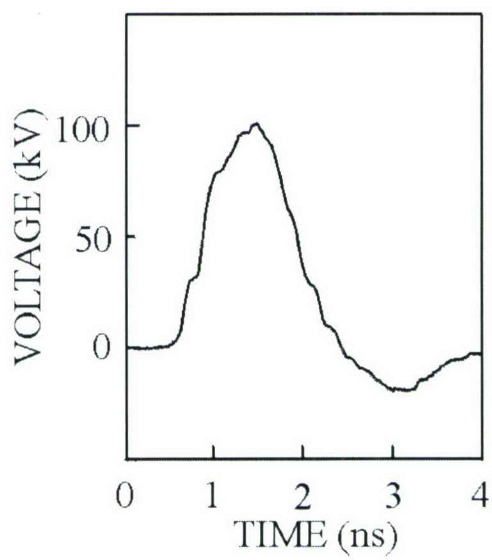

Figure 12. Output voltage waveform generated by a two-line stacked Blumlein prototype pulser commutated with a photoconductive switch.

As seen in Fig. 11, a rapid rise of x-ray pulse should start at the time where the discharge voltage approaches the maximum and should drop off as discharge voltage falls and ceases. Since the pulse rise time available from the photoconductively-switched pulser is on the order of

200 ps, the generated x-ray pulse rise time is expected to be less than 100 ps. In this case the x-ray pulse duration would be about half the discharge voltage pulse width of 1-2 ns.

During this work we studied issues involving the delivery of the fast-rising waveforms to low profile x-ray diodes. Low impedance x-ray diodes designed, studied and implemented. Output waveforms and x-ray generated were examined by the proper matching of diodes to Blumlein pulsers switched with thyratrons and or photoconductive switches. Ultra-fast rising x-ray pulses were produced and studied. An example of a preliminary result is shown in Fig.13 where a nanosecond x-ray pulse with a rise time of about 400 ps is generated. In this case a low impedance diode was matched to a photoconductively switched 2-line stacked Blumlein pulser. More work and optimization of the x-ray diode design are needed to fully characterize x-ray production by photoconductive switching of Blumlein pulsers.

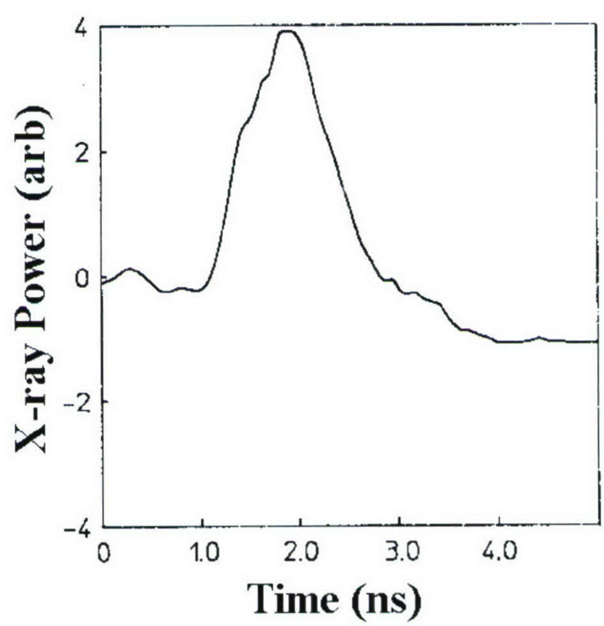

Figure 13. X-ray output emitted from a low profile diode powered by a 2-line stacked Blumlein pulser commutated by a photoconductive switch. This particular data corresponded to an out voltage of 60 kV.

EXECUTIVE SUMMARY

1. Summary of the Results

The research conducted for this program was designed to build upon highly successful efforts in the areas of ultra-fast pulse generation performed at UTD. The principal objective was to enlarge the pulser technology base, level of understanding and design options for generation of high repetition ultra-fast pulses. During this project, efforts were concentrated upon exploration and examinations of the impedance parameter space and output pulse characteristics of the UTD Blumlein devices to facilitate development of reliable pulsers capable of generating intense UWB electric fields for Bioelectrics and Isomer Research applications. Output pulse characteristics available from our Blumlein pulsers with different number of lines, line impedances and switching devices were examined and studied. The range of pulse characteristics that may be of interest for Bioelectric and Isomer Research applications are recorded. The following Table reproduces the summary of output pulse characteristics available from our Blumlein pulsers as investigated in this work. It was determined that the open circuit pulses exhibiting bipolar shapes are available from the Blumlein Pulsers and may be utilized to study bipolar-UWB radiation effects in Bioelectric applications.

Blumlein Pulser Configuration	**Switching Device**	**Output Characteristics**				
		Impedance (Ω)	Pulse Duration (ns)	Pulse Risetime (ns)	Peak Voltage matched (kV)	Peak Voltage Open Circuit (kV)
Single-Line	Thyratron	1- 200	50-100	10-40	5-75	8-140
	Spark Gap	1-200	20-100	4-10	5-75	10-130
	Photoconductive Switch	50-100	1-40	0.15-1	10-60	15-110
2-Line Stacked	Thyratron	40-100	50-600	15-40	10-120	18-180
	Spark Gap	40-100	20-100	5-15	10-110	20-200
	Photoconductive Switch	100-200	1-5	0.2-1	30-120	45-160
3-Line Stacked	Thyratron	60-150	50-100	20-40	15-170	25-300
	Spark Gap	60-150	20-100	5-20	15-170	30-280
4-Line Stacked	Thyratron	80-200	50-100	25-40	20-190	30-350
	Spark Gap	80-200	20-100	8-20	20-195	30-340
	Photoconductive Switch	400	1.5	0.2-0.5	50-150	80-200
6-Line Stacked	Thyratron	120-300	50-100	25-50	30-270	50-500
	Spark Gap	120-300	20-100	8-25	30-260	55-480
8-Line Stacked	Thyratron	160	150	70	40-310	70-420
12-Line Stacked	Thyratron	480	200	75	60-400	100-530

During this program the level of understanding concerning the optimal use of capabilities of the Photoconductive Semiconductor Switches (PCSS) were significantly enlarged. Experiments with the stacked Blumlein prototype pulsers were conducted under different conditions of operation at power levels bypassing 120 MW. Special attention was placed on broadening of the current channels in the avalanche photoconductive switch in order to improve

PCSS lifetime. The following Table presents the best simultaneous results obtained, to date, by switching the stacked Blumlein pulsers with a high gain GaAs photoconductive semiconductor switch (PCSS).

Parameters	Simultaneous Results		
Switch Voltage	60 kV	30 kV	15 kV
Switch Current	1.2 kA	0.6 kA	0.3 kA
Pulse Risetime	200 ps	200 ps	200 ps
R-M-S Jitter	500 ps	500 ps	500 ps
Optical Trigger Energy	300 nJ	300 nJ	300 nJ
Repetition Rate	10 Hz	20 Hz	20 Hz
Electric Field	60 kV/cm	60 kV/cm	60 kV/cm
Stack Voltage	112 kV	57 kV	29 kV
Switch Lifetime	2×10^4 pulses	3×10^5 pulses	4×10^6 pulses

The mechanical and semiconductor properties of amorphic diamond were employed to improve the PCSS longevity by coating the switch cathode or anode areas or both. Issues concerning the switch longevity were studied by fabrication and testing the GaAs PCSS treated with the amorphic diamond under different switch configuration, gap settings, and diamond coating thickness. Longevity tests were performed by coating the cathode and anode areas of a GaAs PCSS with amorphic diamond and testing its performance with a prototype Blumlein pulser. Different switch design options were used. As shown in the following Table, or a switch gap of 2.5 mm, the lifetime was found to be 4×10^6 commutation cycles showing a significant improvement with the application of amorphic diamond.

Test Condition	Switch Lifetime 2.5 mm switch gap
Uncoated Switch	1×10^5 pulses
Diamond coating at anode	5×10^5 pulses
Diamond coating at cathode	1×10^6 pulses
Diamond coatings at both anode and cathode	4×10^6 pulses

In addition, we studied and surveyed various methods and geometries for non-intrusive electric field delivery and flash x-ray production suitable for Bioelectric and Isomer Research applications, respectively. Low impedance x-ray diodes designed, studied and implemented. Output waveforms and x-ray generated were examined by the proper matching of diodes to Blumlein pulsers switched with thyratrons and photoconductive switches. Ultra-fast rising x-ray pulses were produced and studied.

2. Personnel Participated

The professional personnel participated in the research program are listed below:

1)	Carl B. Collins	Professor
2)	Farzin Davanloo	Research Scientist
3)	Ariana D. Paraschiv	Technical Staff Assistant

3. Publications Resulted from this Work

"Progress in Development and Characterization of Photoconductively-Switched Stacked Blumlein Devices Producing High Power Nanosecond Pulses," F. Davanloo, C.B. Collins, F. J. Agee, in Ultera-Wideband, Short Pulse Electromagnetics 6, Edited by E. L. Mokole, M. Kragalott and K. R. Gerlach (Kluwer Academic / Plenum Publishers, New York, 2003), pp 391-400.

"Development and Applications of Pulsed Power Devices at the University of Texas at Dallas," F. Davanloo, C.B. Collins, and F.J. Agee, Proceedings of the 14th IEEE International Pulsed Power Conference (IEEE, Inc. NJ, 2003), pp. 1403-1406.

"Progress in Development and Application of Pulsed Power Devices at the University of Texas at Dallas," F. Davanloo, C. B. Collins, and F. J. Agee, Proceedings of the 15th IEEE International Pulsed Power Conference, Monterey, CA, U.S.A., June 13-17, 2005.

"Ultra-Fast Flash X-ray Pulses Produced by Blumlein Devices, " F. Davanloo, C. B. Collins and F. J. Agee, Nucl. Instrum. Methods B241, 276-280 (2005).

"Development of Ultra-Wideband Pulsers at the University of Texas at Dallas," by F. Davanloo, C. B. Collins, and F. J. Agee, Ultera-Wideband, Short Pulse Electromagnetics 7, Edited by F. Sabath (Springer Science, New York, 2006), pp 459-466.

"Ultra-Fast High Power Waveforms Produced by Blumlein Pulsers with 100 ps Switching , " F. Davanloo, C. B. Collins and F. J. Agee, The 19th International Conference on the Application of Accelerators in Research and Industry, CAARI 2006, Ft. Worth, Texas, U.S.A., August 20-25, 2006.

RESEARCH SIGNIFICANCE AND POTENTIAL APPLICATIONS

During last few years new areas of pulsed power application have been introduced for the field of Bioelectrics [25]. These include biofouling prevention, bacterial decontamination, and medical applications such as electrochemotherapy and gene therapy. These applications are usually classified as outer membrane bioelectric effects. Very recently, a major discovery was reported by

Schoenbach, et al [1] where initial approaches to apply pulsed electric fields to kill cells by apoptosis were investigated. There, it was demonstrated as the applied pulse duration decreases from 300 ns to 10 ns, electric field effects are reduced at the level of the plasma membrane and are focused to the cell interior. If the electric field intensity is high enough apoptosis can be induced as indicated by the reduced size of treated mouse tumors [26]. This type of field-cell interaction using nanosecond pulses with high electric field has potential to affect transport processes across sub-cellular membranes and may be used for gene transfer into cell nuclei. It can also trigger intracellular processes that can be used for cancer treatment by programmed cell death.

The intracellular electromanipulation processes require the development of reliable pulsed power sources that produce electric fields larger than 50 kV/cm at pulse durations into nanosecond range. Photoconductively-switched Blumlein pulse generators characterized during this AFOSR program are most suitable for the intracellular electromanipulations applications in the Bioelectric field because they have low inductance geometry that permits generation of ultra fast nanosecond waveforms easily matched and delivered to the biological loads.

Advances in stacked Blumlein technology for voltage multiplication at UTD, including progress made during this reporting period, also offer exciting possibilities for a variety of ultra-wideband (UWB) applications especially in array UWB and compact UWB sources. Some of these sources are being used for synthetic aperture radar applications that inherently use the frequency content of pulses. At the 100 MW level of power, broad-band sources operating at kiloHertz repetition rates can be conceived that simply match compact pulsed power devices to the radiation impedance of free space.

It should be noted that the utilization of pulse power technology to treat cancer in human subjects ultimately requires non-intrusive methods such as ultra-wideband (UWB) transmitters.

Such devices could be used to provide necessary electric field strengths and durations at a tumor location in human body to promote apoptosis and cancer treatment. Sources employing UWB schemes feature fast rising short pulse width waveforms with broad frequency contents that are suitable for intracellular electromanipulations.

The stacked Blumlein technology offers tremendous advantage for pulser development for such UWB schemes that can provide non-intrusive probe of human body for medical treatments if suitable electric strength and pulse parameters are identified. Ongoing progress made in stacked Blumlein technology also offers significant advantage for the array source concept by reliable delivery of higher voltages to each radiating element than that available with existing photoconductively -switched systems.

Another of the new application currently opening involves the modulation of nuclear properties. Of particular interest are nuclear spin isomers. They store the highest densities of energy possible without nuclear reactions. For example, an isomer of ^{178}Hf stores 2.445 MeV per atom for a shelf life of 31 years [5,6]. However, in nuclear spin isomers the energy is stored electromagnetically so that it would be released as x-rays and γ-rays, if it could be triggered. Progress made in Blumlein technology during our current AFOSR Program offer a unique opportunity to develop flash x-ray capabilities with 100 ps switching. Since the maximum x-ray dose is emitted before the discharge diode current rises to its peak, such table-top device is expected to produce high power repetitive x-ray pulses into below ns range with risetimes on the order of 100 ps. This device could provide non-thermal x-ray illumination of extended isomer absorbers with yields above 10^{20} keV/keV in a short operating time.

The results of studies performed in this work should guide the reliable use of compact pulse power sources commuted with photoconductive switches that can provide subnanosecond high power pulses at kHz repetition rates. Examples of applications that are of interest to civilian sector include: Bioelectrics, microwave dewaxing of casting molds, microwave oil sludge separation, ozone treatment, and selective bond-breaking for destroying toxic materials. The pulse power systems being developed in this work can also be used to commutate a new generation of flash x-ray devices and laser systems capable of generating high power nanosecond pulses.

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